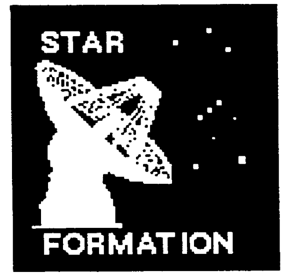
Investigating the Formation of Stars



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Stars precipitate out of the gas/dust clouds of our Galaxy at the rate of about one per year. A qualitative explanation of the process by which this happens was proposed by Kant in 1755 and subsequently elaborated by Laplace in 1796. Quantitatively, we know very much more today, but many fundamental questions remain unanswered. We don't know why stars form at the rate they do. We don't know why there are more small stars (up to a point) than large ones, why there seems to be a cutoff at small masses, what fraction of those stars have planets, and whether the chemical origin for biology developed on Earth, in the preplanetary disk, or in the presolar protostellar nebula.

Observing the formation of stars is a challenge because it happens deep inside dense clouds of gas and dust that are opaque to radiation of wavelengths shorter than about 0.5 mm. In the nearest star-forming regions, concentrations of gas as big as the Sun's Oort cloud of comets (about 30 to 100 times the diameter of Pluto's orbit) have angular sizes of about 20 to 60 arcsec. Only the largest radio telescopes can resolve such objects. By observing the emission from molecular spectral lines, much information can be obtained about the conditions in the protostellar gas.

The temperature of the emitting material is about 6 to 12 K, so that signal levels are weak and large amounts of antenna time are needed to achieve a good signal-to-noise ratio. The antennas of the DSN have proved ideal for this work, being comparable in size to the largest radio telescopes operating at the same frequencies. Over the past three years, we have used DSS-14 at 22 GHz—and DSS-13 time at 45 and 34 GHz—to the problem of how stars form.

We already knew from work by others that large-scale processes concentrate the interstellar molecular gas. Its structure is fractal, and its motions are turbulent. In one of the dense cores of Taurus Molecular Cloud 1 (TMC1), we observed the 22-, 34-, and 45-GHz lines of the molecule dicarbon sulphide (CCS). Figure 1 shows a typical spectrum. The dashed lines represent the emission from three separate clumps along the line of sight, slightly Doppler shifted with respect to each other. We found that this core is a highly fragmented and loosely associated preprotostellar structure. Figure 2 shows a DSS-14 map of some of these fragments. We found that the smallest fragments are internally quiescent, very cold, about the size of the Oort Cloud, and about one-hundredth to one-tenth the mass of the Sun.

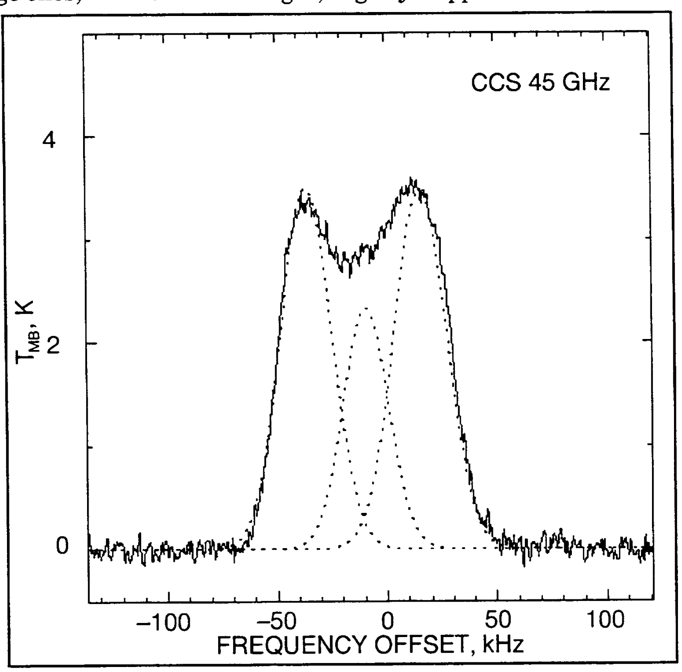

***Figure 1.** A spectrum of the 45-GHz emission of CCS in TMC1.*

In cloud 1498 of Lynds' catalogue (L1498), we found evidence that the coagulation of some of such fragments is building a preprotostellar core. In L1498, we observed that the central region contains

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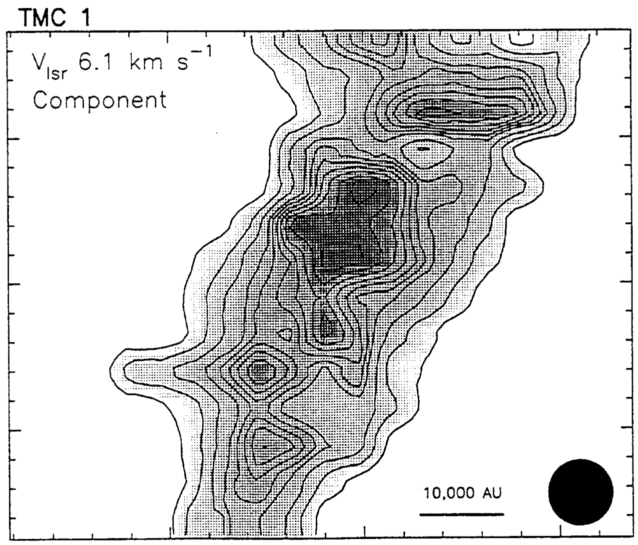


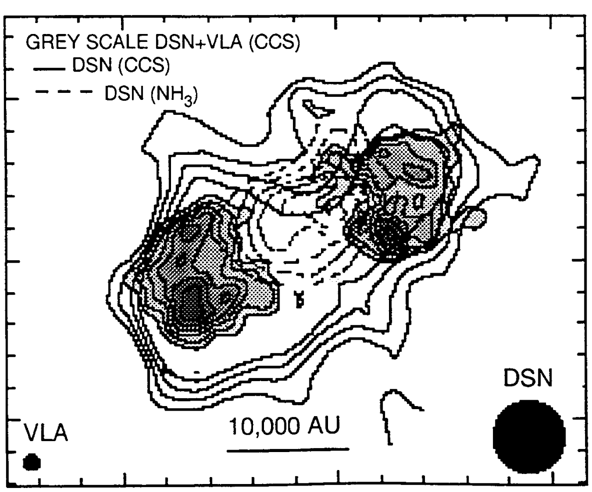
Figure 2. DSS-14 Map of the emission of CCS in TMC1-D with Doppler shifts between 5.65 and 5.75 km/s.

NH_3—relatively old gas by star formation standards (it takes about 10^6 yr to form)—surrounded by a layer of CCS, which has a short lifetime (about 10^5 yr). Figure 3 shows the arclike shape of the CCS emission surrounding the NH_3 emission; this shape became apparent when the DSS-14 data were combined with data from the Very Large Array (VLA) in New Mexico.

After a critical mass is reached, the core collapses. Even after the protostar has formed, material continues to accrete from the surroundings onto the central star and preplanetary disk. A group at the University of Texas at Austin found evidence in the shapes of certain spectral lines that this process is going on at the core of Bok globule 335 (B335). By combining Goldstone 70-m data with data we obtained with the Very Large Array in New Mexico, we imaged young gas in the infalling envelope of B335. We found that the outer part of the infalling envelope was rich in young CCS gas. Figure 4 shows the ringlike distribution of CCS (which is moving perpendicular to our line of sight)—effectively the picture of a slice through the center of the envelope. The distribution is still clumpy, reflecting the structure of the preprotostellar gas we see in L1498 and Taurus Molecular Cloud 1, Core D (TMC1-D).

In the future, we hope to obtain both higher angular resolution and faster data acquisition by using, at 34 GHz, the seven-feed array on DSS-14. We will also investigate the efficiency of some DSN 34-m beam-waveguide antennas at 3 mm wavelength, potentially the largest millimeter-wavelength telescopes in the US.

Figure 3. Composite map of the emission of ammonia and CCS in L1498.



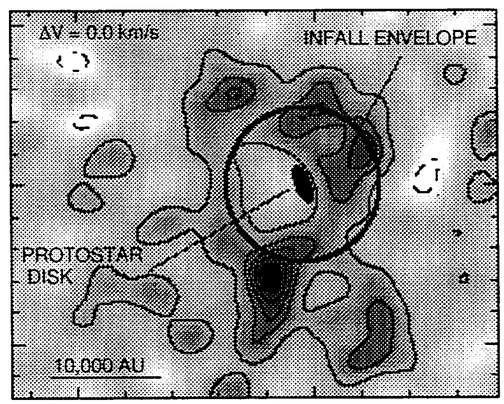


Figure 4. Image of a slice through the center of the collapsing envelope of B335.

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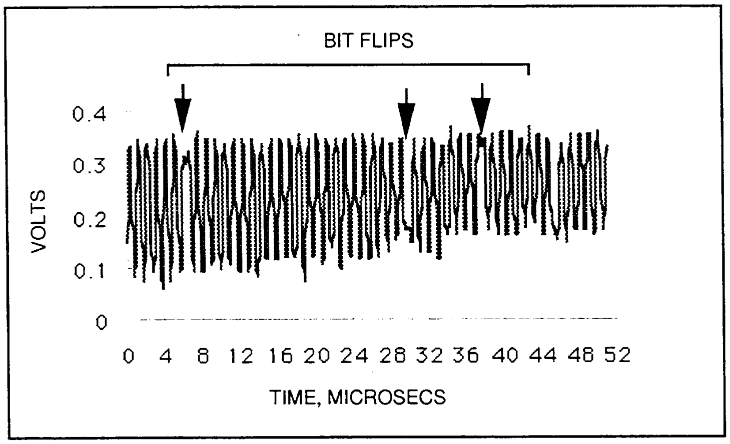

FIGURE 4: THE 128 KBPS DOWNLINKED SATELLITE TELEMETRY WAS REPEATED EIGHT TIMES TO ACHIEVE THE 1.024 MBPS DOWNLINK DATA RATE. DATA SHOWS BIT FLIPS IN MULTIPLES OF EIGHT, CONSISTENT WITH THE 8X REPETITION OF THE BIT PATTERN

PN, regeneration (RX), and E2. The E2 data consist of telemetry from the onboard laser communications equipment sensors. PN mode transmission allowed ready determination of the BER without having to decode E2 data. We have measured downlink BERs as low as 1E-5 during phase-I. Results that are consistent with our predictions based on the measured atmospheric attenuation at TMF (7) and of aperture-averaging of scintillation effects over the large receiver aperture (8).

In the RX mode, the uplink modulation is detected by the onboard optical telecommunications detector. The RX circuitry then recovers the clock, decodes the uplink, and encodes the detected uplink modulation on the downlink. We have demonstrated optical transponder operation by regenerating a 1 MHz square wave transmitted on the optical uplink. We have also recovered several hundred megabytes of E2 data transmitted at 1.024 Mbps. A sample of the data is shown in Figure 4. E2 data is comprised of 128 Kbps telemetry data repeated 8 times to meet the specified 1.024 Mbps data rate. This is shown in the figure where bit flips occur in the downlink data stream in multiples of eight.

GOLD Phase-II demonstrations resumed on March 21, 1996 and are expected to continue to May 26, 1996. Our phase-II objectives are to (i) demonstrate optical ranging, (ii) compare the reduction in scintillation fades of two-beam and four-beam propagation, and (iii) evaluate daytime acquisition approaches. The GOLD, GOPEX, and CEMERLL experiments have been important demonstrations that have allowed us to evaluate our optical communications models. They have also provided opportunities for us to develop operational strategies for ground-to-space and space-to-ground optical communications that can be used in future free space optical communications.

References

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